

Universal logical operations in a silicon quantum processor

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Quantum errors induced by environmental noise are unavoidable and preclude the direct implementation of practical quantum computation. Fault-tolerant quantum computation offers one of the viable paths, necessitating the encoding and processing of information within logical qubits to curb such errors. Although substantial progress has been achieved recently in building silicon quantum computers, logical operations still haven't been realized in silicon. Here we demonstrate a logical quantum processor using a phosphorus donor cluster in silicon. By implementing the $[[4, 2, 2]]$ code, we realize the essential components for logical operations, which include fault-tolerant preparation of logical states and the characterization of a universal gate set comprising logical single-qubit and two-qubit gates. In particular, the logical T gate is achieved using the gate-by-measurement method, and magic states based on this gate are prepared. Furthermore, we execute the variational quantum eigensolver algorithm using two logical qubits and simulate the ground state of the electronic structure of the water molecule H_2O . This work represents a key step towards scalable, fault-tolerant quantum computation in silicon spin qubits.

Silicon-based spin qubits^{1,2} have emerged as a promising platform for scalable quantum computing, combining complementary metal-oxide-semiconductor (CMOS)-compatible fabrication technologies alongside the long quantum coherence times intrinsic to electron and nuclear spins in isotopically purified ^{28}Si . Recent advances highlight the potential of silicon qubit platforms for scalable quantum processors, including quantum gate fidelities above the fault-tolerance threshold^{3–6}, seminal attempts at quantum error correction^{7,8} and early-stage multi-qubit integration^{9–12}. Additionally, initial endeavours

to develop a quantum computing system-on-chip have also been undertaken, showcasing qubits operating above 1 K (refs. 13–16), cryo-CMOS chips rivalling the control precision of room-temperature instruments¹⁷ and a heterogeneous ‘chiplet style’ integrated quantum computing system-on-chip prototype¹⁸. As one of the major technical approaches in silicon, donor-based spin qubits occupy a unique niche, offering atomic-scale qubits and long coherence times¹⁹. Although challenges remain in atomic-scale device fabrication compared with gate-defined quantum dots, advances in donor systems now

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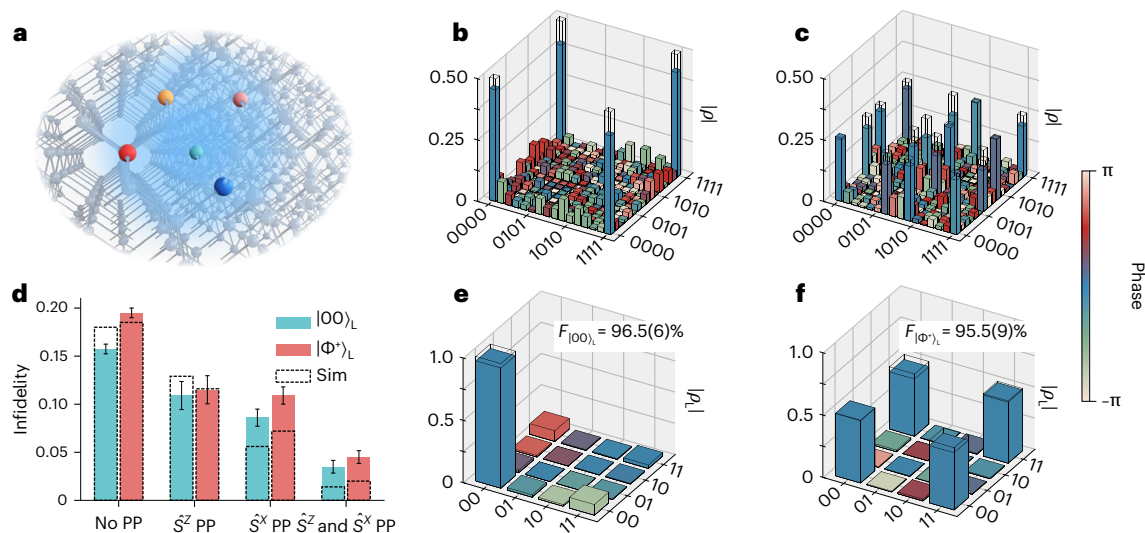


Fig. 1 | The donor cluster and preparation of the logical states. **a**, The schematic of a donor cluster with five ^{31}P nuclei in a ^{28}Si lattice. As detailed in our previous work⁴⁰, the hyperfine interactions (A) between the shared electron (light blue background) and each nucleus (marked in different colours) are $A_1 = 28.6$ MHz, $A_2 = 73.7$ MHz, $A_3 = 137.0$ MHz, $A_4 = 226.0$ kHz and $A_5 = 168.0$ kHz. Those hyperfine interactions enable high-connectivity CCCZ-type gates within one cluster. **b, c**, Experimental reconstructed density matrices ρ for the logical state $|00\rangle_L$ (**b**) and the logical Bell state $|\Phi^+\rangle_L$ (**c**), obtained via quantum state tomography (Methods). **d**, The infidelity of the logical $|00\rangle_L$ and Bell $|\Phi^+\rangle_L$ states,

for the raw data, after $\hat{S}^Z$ PP, $\hat{S}^X$ PP and both of them, where PP is the parity projection. Compared with the raw data, the error can be suppressed over four times. The dashed wireframes in **d** depict results from master equation simulation (Sim). **e, f**, Postprocessed logical density matrices ρ_L of logical $|00\rangle_L$ (**e**) and logical $|\Phi^+\rangle_L$ (**f**) after the PP on both $\hat{S}^Z$ and $\hat{S}^X$ stabilizers. The wireframes in **b, c, e** and **f** represent ideal results. In **b–f**, each basis for quantum state tomography comprises at least 300 measurement repetitions. All error bars are estimated via Monte Carlo bootstrap resampling and represent one standard deviation (1 s.d.) from the mean.

encompass high-fidelity quantum gate operations⁵, multi-qubit circuit demonstrations^{5,20}, exchange-coupling-assisted multi-qubit gates between donor clusters¹² and the exploitation of high-dimensional nuclear spin qubit states²¹—collectively positioning donor qubits as a compelling pathway towards a scalable, silicon-based quantum computing platform.

Physical qubits in solid-state platforms^{1,22} are susceptible to environmental noise, which originates from multiple sources, including phonon interactions, nuclear spin fluctuations and charge noise. In silicon-based quantum processors, frequency crowding and cross-talk^{23–26} further exacerbate the errors as the system scales. To address these errors, logical encoding stands as the only viable solution by redundantly storing quantum information across multiple physical qubits^{27,28}. While logical qubits and operations have been successfully demonstrated in platforms such as superconducting circuits^{29,30}, neutral atoms³¹, nitrogen-vacancy centres³² and trapped ions³³, their implementation in silicon-based spin qubits poses notable technical challenges. This is due to the need to simultaneously realize multi-qubit entanglement, deep circuit depth and multi-qubit measurements. Recently, two research groups have made pioneering advances towards fault-tolerant quantum computation (FTQC) by demonstrating phase error correction via coherent conditional rotations^{7,8}. However, fault-tolerant (FT) encoding and universal logical operations have yet to be realized in silicon-based spin qubits.

The $[[4, 2, 2]]$ code^{34–36} has been highlighted by Gottesman for its minimal resource requirements in demonstrating quantum fault tolerance³⁶. The code enables FT encoding of two logical qubits on only five physical qubits, with one serving as an ancillary that is not involved in the encoding³⁶. Furthermore, it allows FT single-qubit and two-qubit Clifford logical gates, making the $[[4, 2, 2]]$ code an ideal building block for scalable quantum computing architectures. As FTQC becomes mainstream in quantum computing research, the $[[4, 2, 2]]$ code has become increasingly prominent^{31,37}. Although this code cannot correct an arbitrary single-qubit error, it functions as the inner code in concatenated higher-level error-correction schemes³⁸,

which can substantially reduce resource overhead by orders of magnitude and lower the FT threshold in large-scale quantum computing³⁹.

Here we demonstrate a logical quantum processor based on the $[[4, 2, 2]]$ code using five nuclear spins in a silicon donor system¹⁹. The FT logical state is prepared and a complete set of universal logical gates is demonstrated, including single-qubit and two-qubit gate operations, in a donor cluster. All Clifford gates are implemented using native physical quantum gates, while the T gate is realized through the gate-by-measurement method. Finally, we execute a variational quantum eigensolver (VQE) algorithm on two logical qubits using logical operations to compute the ground-state energy of a water molecule, H_2O .

Logical state preparation

In this work we employ scanning tunnelling microscopy (STM) lithography to fabricate our device on a $\text{Si}(100)\text{-}2 \times 1$ surface. Following the lithography patterning, phosphorus atoms are doped into the opened windows and incorporated in subsequent processing. After the overgrowth of an epitaxial capping layer, the atomic device is embedded between the epitaxially grown ^{28}Si layers. The device contains three donor cluster dots, though only the right one is used in this experiment, which consists of five phosphorus atoms (see Fig. 1a) and one fortuitously incorporated hydrogen atom. The average electron spin read-out fidelity for the right dot is estimated to be $\sim 81.45\%$, and further details can be found in our previous work⁴⁰. The five phosphorus nuclear spins are used for implementing the logical quantum circuits, while the hydrogen nuclear spin is initialized to a fixed spin-up state. The calibrated system parameters can be found in Supplementary Tables 1 and 2 of Supplementary Section 5. The state preparation and measurement (SPAM) error characterization and physical gate fidelity benchmarks are presented in Extended Data Figs. 1 and 2.

Nuclear spins serve as qubits in our system. The native gate set comprises single-qubit gates realized through nuclear magnetic resonance (NMR) and CCCZ-type gates implemented via electron spin resonance (ESR). Single-qubit addressability is enabled by distinct hyperfine

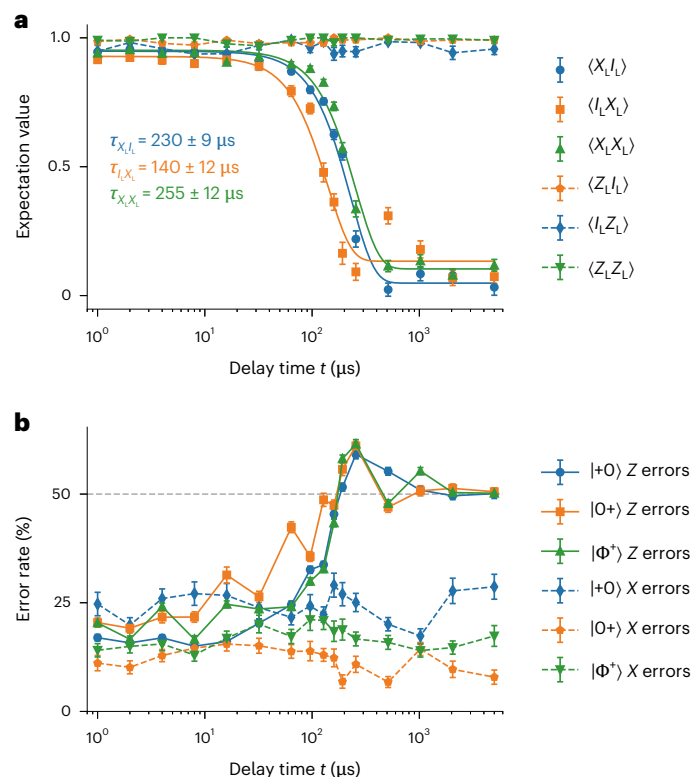


Fig. 2 | Logical coherence times and error rates. a, The logical coherence times and lifetimes are characterized, where the expectation values $\langle X_L I_L \rangle$ and $\langle I_L Z_L \rangle$ are measured on $|+0\rangle_L$, $\langle I_L X_L \rangle$ and $\langle Z_L I_L \rangle$ on $|0+\rangle_L$ and $\langle X_L X_L \rangle$ and $\langle Z_L Z_L \rangle$ on $|\Phi^+\rangle_L$. Since our qubits are encoded on nuclear spins, the expectation values of $Z_L I_L$, $I_L Z_L$ and $Z_L Z_L$ remain stable without observable decay throughout the measurement duration, reflecting their inherently long lifetimes. **b**, The error rates are obtained through postprocessing of stabilizer parity checks (Supplementary Section 8 contains details). The qubit flip error (X), detected by the stabilizer $\hat{S}^Z$, remains at its initial value. By contrast, the phase-flip error (Z), detected by the stabilizer $\hat{S}^X$, increases as the physical qubits decohere versus delay time t . Each data point is averaged over 1,000 experimental repetitions. Error bars represent 1 s.d. from the mean, estimated via bootstrap resampling.

coupling of each nuclear spin, which varies depending on their atomic configurations within the cluster. The CCCCZ-type gates are realized via driving the corresponding ESR transition of a specific nuclear spin configuration^{5,12,20}. Consequently, an ESR 2π pulse induces a geometrical π phase, enabling electron-mediated nuclear spin CCCCZ-type gates. These gates offer high connectivity and high efficiency in quantum circuit compiling, which could be used to reduce circuit complexity⁴¹. However, some ESR driving frequencies could be closely spaced due to near-degenerate hyperfine couplings, necessitating cross-talk suppression techniques (detailed in Supplementary Section 11).

To prepare the logical two-qubit states, we compile the logical state preparation circuits for logical state $|00\rangle_L$ and Bell state $|\Phi^+\rangle_L$ using our native gate set. Both circuits use four physical qubits, with their compiled implementations and error propagation analysis detailed in Supplementary Section 6. The prepared states $|00\rangle_L$ and $|\Phi^+\rangle_L$ are measured in the physical qubit basis (the corresponding expectation values under different bases for $|00\rangle_L$ state reconstruction are provided in Extended Data Fig. 3), and their corresponding state tomography results are shown in Fig. 1b,c, yielding initial physical fidelities of 84.2(5)% and 80.5(7)%, respectively (the representation of the uncertainty is explained in Methods).

The $[[4, 2, 2]]$ code has stabilizers $\hat{S}^X = X_1 X_2 X_3 X_4$ and $\hat{S}^Z = Z_1 Z_2 Z_3 Z_4$ (X, Y and Z denote the corresponding Pauli operators across this paper). Since we cannot perform mid-circuit measurements, stabilizer parity projections are implemented via postprocessing at the end of circuits

in a destructive manner. After postprocessing with $\hat{S}^Z$ and $\hat{S}^X$ parity projections and removing detected errors, the state fidelities of $|00\rangle_L$ and $|\Phi^+\rangle_L$ in the logical space increased to 96.5(6)% and 95.5(9)%, as shown in Fig. 1d, with acceptance ratios of 83.9(13)% and 82.9(17)%, respectively. Their converted state density matrices on the logical basis are depicted in Fig. 1e,f. Error analysis reveals that the logical error originates mainly from cross-talk-induced higher-weight errors, which lie beyond the error detection capability of the $[[4, 2, 2]]$ code. In addition, we prepared the logical state $|00\rangle_L$ in a circuit that has a similar spirit, proposed by Gottesman with a flag qubit³⁶, achieving a logical fidelity of 97.3(7)% after postprocessing with both stabilizers conditioned on the flag not being raised (Extended Data Fig. 4).

Next we characterize the logical coherence times by measuring the expectation values of the logical operators $X_L I_L$, $I_L X_L$ and $X_L X_L$ as a function of delay time τ (ref. 42). The results for different logical states are displayed in Fig. 2a, and by fitting with the approximately exponential decay, we obtain logical coherence times as $\tau_{X_L I_L} = 230(9) \mu\text{s}$, $\tau_{I_L X_L} = 140(12) \mu\text{s}$ and $\tau_{X_L X_L} = 255(12) \mu\text{s}$ which are related to the logical qubit L_1 with $|+0\rangle_L$, logical qubit L_2 with $|0+\rangle_L$ and their entangled state with $|\Phi^+\rangle_L$, respectively. The average coherence time for physical qubits (except N_4 and N_5) is approximately 523 μs , while the average coherence time for logical qubits is around 208 μs , which is shorter than that of all the physical qubits. This reduction arises because the two logical qubits are, by their nature, a four-qubit entangled state that is inherently more susceptible to decoherence compared with any individual physical qubit. Notably, the measurement results in Fig. 2b reveal a strong noise bias in the system, with phase-flip (Z) errors dominating bit-flip (X) errors. Based on previous theoretical works, the biased noise can be beneficial in improving the fault-tolerance threshold, thereby reducing the physical qubit overhead and simplifying scalable architectures⁴³.

Universal logical gate set

We implement a universal logical gate set, comprising single-qubit gates X_L , S_L and T_L , the simultaneous single-qubit gate $H_L H_L$ and the

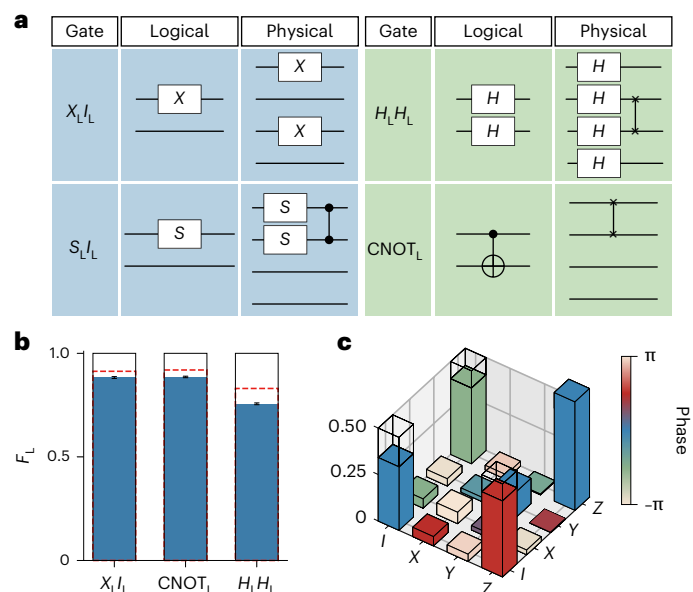


Fig. 3 | Logical gates for the $[[4, 2, 2]]$ code. a, Circuits for the logical Clifford gates of the $[[4, 2, 2]]$ code, comprising $X_L I_L$, $S_L I_L$, $H_L H_L$ and CNOT_L . The corresponding logical circuits are shown in the middle column, and their equivalent physical circuits are displayed in the last column. **b**, Measured population transfer fidelities of logical gates $X_L I_L$, CNOT_L and $H_L H_L$, where the red dashed bars represent the simulation results. **c**, The QPT result for the $S_L I_L$ gate on the first logical qubit. For different input states, the resulting density matrices are measured after applying the $S_L I_L$ gate, achieving a QPT fidelity of 87.0(16)%. The wireframes depict the ideal results.

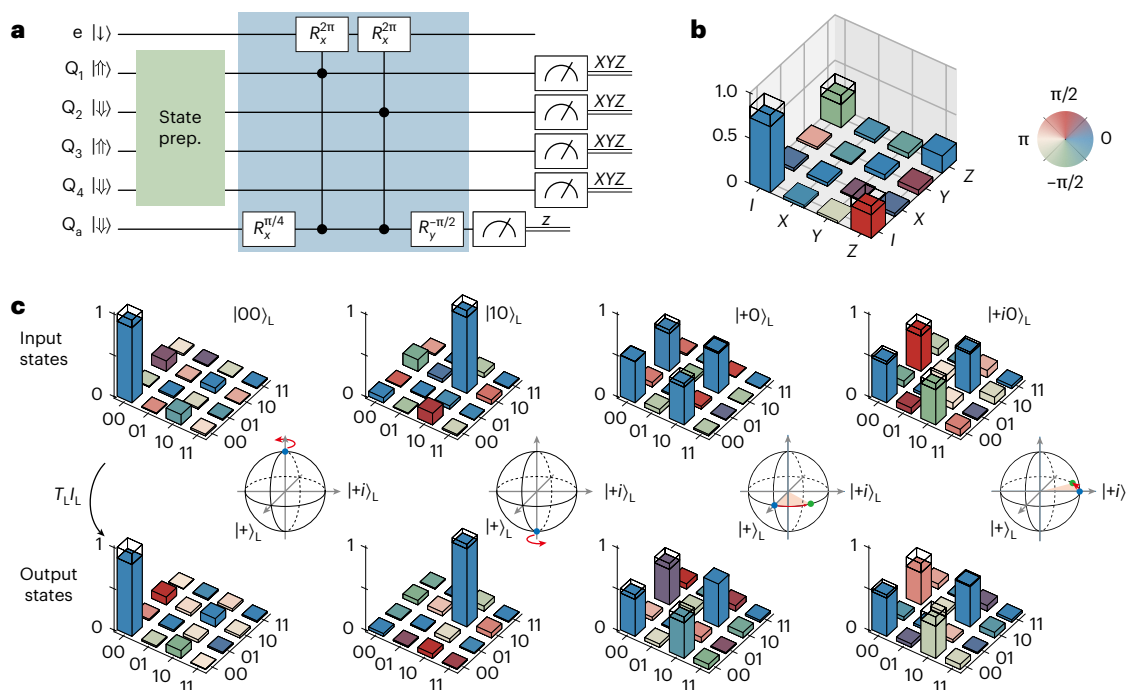


Fig. 4 | QPT for the $T_L I_L$ gate. a, Circuit for QPT of the $T_L I_L$ on the first logical qubit L , where ‘State prep.’ denotes state preparation and the four logical cardinal states $\{|00\rangle_L, |10\rangle_L, |+0\rangle_L, |+i0\rangle_L\}$ are prepared as inputs. The logical gate is implemented via the gate-by-measurement method using an extra ancillary nuclear spin. **b**, Experimental (solid) and ideal (wireframe) QPT matrices

conditioned on ancillary measurement outcome $|0\rangle$, giving a $T_L I_L$ gate process fidelity of 82.6(23)%. **c**, Logical state tomography of input and output states of the $T_L I_L$ gate. The inset Bloch spheres display the initial states (blue dots) and final states (green dots) under the $T_L I_L$ gate operation in the logical code space. The wireframes depict ideal values.

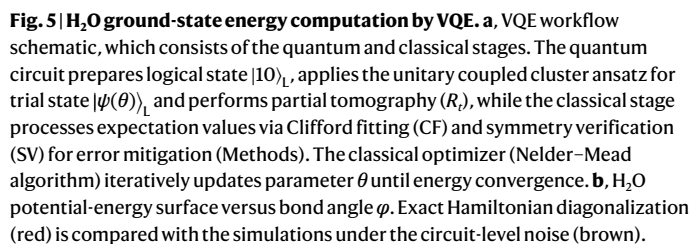
two-qubit gate $CNOT_L$. Since the circuits for demonstrating logical single-qubit gates on either logical qubit are similar, here we perform those operations on the first logical qubit as an example, labelled as $X_L I_L$, $S_L I_L$ and $T_L I_L$. The implementation circuits for those logical Clifford gates are listed in Fig. 3a, where the physical single-qubit operations are realized via NMR pulses, the physical CZ gate is executed by the corresponding CCCCZ gate and SWAP gates in the $H_L H_L$ and $CNOT_L$ circuits are virtually applied through qubit relabelling (Supplementary Section 15 contains the compiled circuits). Notably, in the compiled circuits, the gates $X_L I_L$, $H_L H_L$ and $CNOT_L$ are FT, whereas the $S_L I_L$ gate is non-FT (nFT).

The FT logical gates $X_L I_L$, $H_L H_L$ and $CNOT_L$ are characterized by their population transfer fidelity $F_L = \text{Tr}(M_{\text{exp}} M_{\text{ideal}}^{-1})$ in the logical space, where M_{exp} and M_{ideal} represent the experimental and ideal population transfer matrices in the logical basis, respectively. For $X_L I_L$ and $CNOT_L$, the initial states are $|00\rangle_L, |01\rangle_L, |10\rangle_L$ and $|11\rangle_L$; for $H_L H_L$, the initial states are $|++\rangle_L, |+-\rangle_L, |-+\rangle_L$ and $|--\rangle_L$. The resulting state transfer matrices M_{exp} can be found in Extended Data Fig. 5, and the corresponding population transfer fidelities for $X_L I_L$, $CNOT_L$ and $H_L H_L$ are 88.3(5)%, 88.6(4)% and 75.6(4)%, respectively. The average fidelity of both physical single-qubit and two-qubit gates exceeds 95%, whereas the average fidelity for logical single-qubit and two-qubit gates is approximately 86%. This discrepancy arises because the error from the initial logical state preparation circuits was not subtracted during the characterization of the logical gates (Fig. 3b; Supplementary Section 16 has details).

The $S_L I_L$ gate essentially realizes a $\pi/2$ -phase σ_z rotation on the first logical qubit. We used the gate process tomography to calibrate the $S_L I_L$ gate, with $|00\rangle_L, |10\rangle_L, |+0\rangle_L$ and $|+i0\rangle_L$ as the initial input states. The italic i denotes the imaginary unit. In the state definition: $|+i\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$; this represents the eigenstate of the Pauli-Y operator, corresponding to the $+Y$ axis on the Bloch sphere. Figure 3c presents the quantum process tomography (QPT) results (details shown in Extended Data Fig. 6), revealing an 87.0(16)% gate process fidelity. Across all the logical gates, the experimental results align well with our master equation simulations, with residual cross-talk identified as the dominant error source.

While Clifford gates are essential, universal quantum computing necessitates the inclusion of non-Clifford gates; otherwise, the computation can be efficiently simulated classically, as per the Gottesman–Knill theorem⁴⁴. To complete our universal logical gate set, we implement a logical $T_L I_L$ gate using the gate-by-measurement method³⁰, which is crucial for achieving FTQC. As shown in Fig. 4a, the circuit employs five nuclear spins, using an ancillary nuclear spin (Q_a) to inject the $T_L I_L$ and $T_L^\dagger I_L$ gate onto the target logical qubit (L) via controlled operations. Specifically, the ancillary read-outs $|0\rangle$ and $|1\rangle$ correspond to a $T_L I_L$ and $T_L^\dagger I_L$ gate for a $\pi/4$ and $-\pi/4$ Z rotation, respectively. Here we postselect the ancillary $|0\rangle$ outcomes to evaluate the $T_L I_L$ gate, where the QPT reveals a fidelity of 82.6(23)% (Fig. 4b). Meanwhile, the $T_L^\dagger I_L$ gate QPT fidelity is measured as 91.5(24)% (Extended Data Fig. 7). We further verify the functionality of the $T_L I_L$ gate by applying it to different input logical cardinal states and performing output state tomography, with results shown in Fig. 4c. In addition, Extended Data Table 1 provides all corresponding logical state characterization results.

Magic states are indispensable resources for achieving universal FT gate sets, and high-fidelity magic states can be purified through distillation⁴⁵. Notably, the $T_L I_L$ and $T_L^\dagger I_L$ gates we implement directly generate H -type equivalent magic states when applied to $|+0\rangle_L$ and $|+i0\rangle_L$. The resulting states are defined as follows: $|H_1\rangle = T_L I_L |+0\rangle_L$, $|H_2\rangle = T_L^\dagger I_L |+0\rangle_L$, $|H_3\rangle = T_L I_L |+i0\rangle_L$ and $|H_4\rangle = T_L^\dagger I_L |+i0\rangle_L$, and their corresponding state tomography reveals magic-state fidelities of 89.8(21)%, 89.7(23)%, 84.0(23)% and 95.2(19)%, respectively. The fidelities of magic state $|H_4\rangle$ surpass the distillation threshold of 92.7% for H -type states, which enables the universal quantum computation through the adaptive magic-state distillation protocol proposed by Bravyi and Kitaev⁴⁵. Furthermore, we quantify the amount of magic using stabilizer 2-Rényi entropy⁴⁶, for which the theoretical maximum is 0.415 for H -type magic states and 0.585 for T -type magic states. Our $|H_1\rangle, |H_2\rangle, |H_3\rangle$ and $|H_4\rangle$ states yield magic values of 0.445(15), 0.420(32), 0.402(22) and 0.445(13), respectively, confirming the magic produced by our quantum circuit. The slight deviations above the theoretical



Error-mitigated outcomes using parity check (blue circle), CF (blue diamond) and CF + SV (blue square) approach theoretical values. **c**, Energy discrepancy (brown) between simulation and theory, and discrepancies (blue circle, diamond and square) between experiments and theory in **b**. In **b** and **c**, each data point is obtained from at least 500 experimental repetitions. Error bars are estimated via Monte Carlo bootstrap resampling and represent 1 s.d. from the mean. **d**, Iteration process at 100.8° (Extended Data Fig. 8 for other angles). VQE reaches an energy deviation $\Delta E \leq 0.02$ Ha and $\Delta \theta \leq 0.01$ rad within 30 iterations, balancing accuracy with convergence speed in the iterative process.

In the circuit, the two logical qubits are initialized in the Hartree-Fock state $|\Phi\rangle$, with the equivalent $R_y(\theta)$ rotation on the first logical qubit

Figure 5b displays the measured energy as a function of the bond angle φ , revealing the optimal configuration at $\varphi = 110^\circ$ with the corresponding ground-state energy of $-74.940(6)$ Ha. Although reaching a chemical precision comparable to that of the full configuration interaction method requires at least 11 qubits⁴⁸, our VQE experimental results show remarkable agreement with the theoretical values (red dashed curve) by considering only the first excited term in the truncated Hamiltonian Trotter expansion. The experimental results (blue squares) exhibit an average difference of 22.7 mHa from the theoretical values. Additionally, we perform numerical simulations of the master equation accounting for cross-talk and decoherence, which results in a mean deviation of 13.3 mHa from the theoretical values (Fig. 5c; also Extended Data Fig. 9). In summary, our results demonstrate a successful

VQE implementation using logical states in a silicon qubit platform. In the future, by reducing the cross-talk and expanding the system with more logical qubits, we anticipate achieving high-precision results surpassing the chemical precision for larger molecules.

Conclusion

This work demonstrates FT logical-state preparation and universal logical gate operations in a silicon donor system with five nuclear spins by using $[[4, 2, 2]]$ logical encoding. We successfully executed a VQE algorithm to calculate the water ground energy and showcase the application of logical operations. Additionally, the logical qubit coherence time measurements reveal strongly biased noise, which will be beneficial for greatly lowering the fault-tolerance threshold of physical gate fidelities. Moving forward, we aim to explore better donor engineering techniques and pulse engineering approaches to reduce cross-talk in this system. Specifically, donor engineering requires high-precision atomic placement. This represents a key technical challenge, and substantial ongoing research efforts are needed to address it (details in Supplementary Section 4). Moreover, donor cluster arrays will be fabricated to scale this system up and realize the FTQC architecture, where the donor cluster arrays can be flexibly reconfigured to accommodate different FT encodings⁵¹. We envision tailored FTQC schemes for the system by using the features demonstrated in this work, including high-connectivity Toffoli gates, strongly biased noise and logical states encoded in clusters. This work marks a transition from physical qubit operation to FT logical encoding in silicon quantum computing.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41565-026-02140-1>.

References

- Burkard, G., Ladd, T. D., Pan, A., Nichol, J. M. & Petta, J. R. Semiconductor spin qubits. *Rev. Mod. Phys.* **95**, 025003 (2023).
- Zwanenburg, F. A. et al. Silicon quantum electronics. *Rev. Mod. Phys.* **85**, 961–1019 (2013).
- Noiri, A. et al. Fast universal quantum gate above the fault-tolerance threshold in silicon. *Nature* **601**, 338–342 (2022).
- Xue, X. et al. Quantum logic with spin qubits crossing the surface code threshold. *Nature* **601**, 343–347 (2022).
- Mądzik, M. T. et al. Precision tomography of a three-qubit donor quantum processor in silicon. *Nature* **601**, 348–353 (2022).
- Mills, A. R. et al. Two-qubit silicon quantum processor with operation fidelity exceeding 99%. *Sci. Adv.* **8**, eabn5130 (2022).
- Takeda, K., Noiri, A., Nakajima, T., Kobayashi, T. & Tarucha, S. Quantum error correction with silicon spin qubits. *Nature* **608**, 682–686 (2022).
- van Riggelen, F. et al. Phase flip code with semiconductor spin qubits. *npj Quantum Inf.* **8**, 124 (2022).
- Philips, S. G. J. et al. Universal control of a six-qubit quantum processor in silicon. *Nature* **609**, 919–924 (2022).
- Wang, C.-A. et al. Operating semiconductor quantum processors with hopping spins. *Science* **385**, 447–452 (2024).
- Weinstein, A. J. et al. Universal logic with encoded spin qubits in silicon. *Nature* **615**, 817–822 (2023).
- Edlbauer, H. et al. An 11-qubit atom processor in silicon. *Nature* **648**, 569–575 (2025).
- Petit, L. et al. Universal quantum logic in hot silicon qubits. *Nature* **580**, 355–359 (2020).
- Yang, C. H. et al. Operation of a silicon quantum processor unit cell above one kelvin. *Nature* **580**, 350–354 (2020).
- Camenzind, L. C. et al. A hole spin qubit in a fin field-effect transistor above 4 kelvin. *Nat. Electron.* **5**, 178–183 (2022).
- Huang, J. Y. et al. High-fidelity spin qubit operation and algorithmic initialization above 1 K. *Nature* **627**, 772–777 (2024).
- Xue, X. et al. CMOS-based cryogenic control of silicon quantum circuits. *Nature* **593**, 205–210 (2021).
- Bartee, S. K. et al. Spin-qubit control with a milli-kelvin CMOS chip. *Nature* **643**, 382–387 (2025).
- Morello, A., Pla, J. J., Bertet, P. & Jamieson, D. N. Donor spins in silicon for quantum technologies. *Adv. Quantum Technol.* **3**, 2000005 (2020).
- Thorvaldson, I. et al. Grover’s algorithm in a four-qubit silicon processor above the fault-tolerant threshold. *Nat. Nanotechnol.* **20**, 472–477 (2025).
- Yu, X. et al. Schrödinger cat states of a nuclear spin qubit in silicon. *Nat. Phys.* **21**, 362–367 (2025).
- Heinrich, A. J. et al. Quantum-coherent nanoscience. *Nat. Nanotechnol.* **16**, 1318–1329 (2021).
- Tanttu, T. et al. Assessment of the errors of high-fidelity two-qubit gates in silicon quantum dots. *Nat. Phys.* **20**, 1804–1809 (2024).
- Lawrie, W. I. L. et al. Simultaneous single-qubit driving of semiconductor spin qubits at the fault-tolerant threshold. *Nat. Commun.* **14**, 3617 (2023).
- Heinz, I. & Burkard, G. Crosstalk analysis for simultaneously driven two-qubit gates in spin qubit arrays. *Phys. Rev. B* **105**, 085414 (2022).
- Undseth, B. et al. Nonlinear response and crosstalk of electrically driven silicon spin qubits. *Phys. Rev. Appl.* **19**, 044078 (2023).
- Shor, P. W. Scheme for reducing decoherence in quantum computer memory. *Phys. Rev. A* **52**, R2493–R2496 (1995).
- Gottesman, D. An introduction to quantum error correction and fault-tolerant quantum computation. Preprint at <https://arxiv.org/abs/0904.2557> (2009).
- Google Quantum AI and collaborators. Quantum error correction below the surface code threshold. *Nature* **638**, 920–926 (2025).
- Marques, J. F. et al. Logical-qubit operations in an error-detecting surface code. *Nat. Phys.* **18**, 80–86 (2022).
- Bluvstein, D. et al. Logical quantum processor based on reconfigurable atom arrays. *Nature* **626**, 58–65 (2024).
- Abobeih, M. H. et al. Fault-tolerant operation of a logical qubit in a diamond quantum processor. *Nature* **606**, 884–889 (2022).
- Postler, L. et al. Demonstration of fault-tolerant universal quantum gate operations. *Nature* **605**, 675–680 (2022).
- Vaidman, L., Goldenberg, L. & Wiesner, S. Error prevention scheme with four particles. *Phys. Rev. A* **54**, R1745–R1748 (1996).
- Grassl, M., Beth, T. & Pellizzari, T. Codes for the quantum erasure channel. *Phys. Rev. A* **56**, 33–38 (1997).
- Gottesman, D. Quantum fault tolerance in small experiments. Preprint at <https://arxiv.org/abs/1610.03507> (2016).
- Reichardt, B. W. et al. Fault-tolerant quantum computation with a neutral atom processor. Preprint at <https://arxiv.org/abs/2411.11822> (2025).
- Knill, E. Quantum computing with realistically noisy devices. *Nature* **434**, 39–44 (2005).
- Yoshida, S., Tamiya, S. & Yamasaki, H. Concatenate codes, save qubits. *npj Quantum Inf.* **11**, 88 (2025).
- Zhang, C. et al. Quantum error detection in a silicon quantum processor. *Nat. Electron.* (2026).
- Rasmussen, S. E., Groenland, K., Gerritsma, R., Schoutens, K. & Zinner, N. T. Single-step implementation of high-fidelity n -bit Toffoli gates. *Phys. Rev. A* **101**, 022308 (2020).
- Krinner, S. et al. Realizing repeated quantum error correction in a distance-three surface code. *Nature* **605**, 669–674 (2022).
- Tuckett, D. K., Bartlett, S. D., Flammia, S. T. & Brown, B. J. Fault-tolerant thresholds for the surface code in excess of 5% under biased noise. *Phys. Rev. Lett.* **124**, 130501 (2020).

44. Gottesman, D. The Heisenberg representation of quantum computers. Preprint at <https://arxiv.org/abs/quant-ph/9807006> (1998).
45. Bravyi, S. & Kitaev, A. Universal quantum computation with ideal Clifford gates and noisy ancillas. *Phys. Rev. A* **71**, 022316 (2005).
46. Oliviero, S. F. E., Leone, L., Hama, A. & Lloyd, S. Measuring magic on a quantum processor. *npj Quantum Inf.* **8**, 148 (2022).
47. McArdle, S., Endo, S., Aspuru-Guzik, A., Benjamin, S. C. & Yuan, X. Quantum computational chemistry. *Rev. Mod. Phys.* **92**, 015003 (2020).
48. Nam, Y. et al. Ground-state energy estimation of the water molecule on a trapped-ion quantum computer. *npj Quantum Inf.* **6**, 33 (2020).
49. Urbanek, M., Nachman, B. & de Jong, W. A. Error detection on quantum computers improving the accuracy of chemical calculations. *Phys. Rev. A* **102**, 022427 (2020).
50. Guo, S. et al. Experimental quantum computational chemistry with optimized unitary coupled cluster ansatz. *Nat. Phys.* **20**, 1240–1246 (2024).
51. Zhang, S. et al. A quantum computer based on donor-cluster arrays in silicon. Preprint at <https://arxiv.org/abs/2509.24749> (2025).

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Methods

Device fabrication

The qubit device was fabricated on an isotopically purified ^{28}Si buffer layer (20 nm thick), epitaxially grown at 380 °C via ultrahigh-vacuum electron-beam deposition on a p-type natural silicon substrate (50–100 $\Omega\text{ cm}$). This layer maintains a ^{29}Si concentration below 130 ppm, effectively isolating qubits from the nuclear spin bath of the natural silicon substrate and enhancing spin coherence times. Using STM-assisted hydrogen depassivation lithography at 77 K (Scienta Omicron INFINITY SPM Lab), we deterministically patterned the hydrogen-passivated silicon surface with atomic precision. The exposed regions were then dosed with phosphine (PH_3) at 5×10^{-7} mbar for 5 min (room temperature), followed by thermal incorporation at 330 °C for 1 min to activate phosphorus donors. This process creates three tunnel-coupled quantum dot structures (P-atom clusters) positioned 17.0 nm away from a single-electron transistor charge sensor for individual qubit addressability and read-out. Subsequently, the doped nanostructure was encapsulated with a 20 nm epitaxial ^{28}Si capping layer, grown at 250 °C (0.7 nm h^{-1} growth rate). This low-temperature epitaxial process ensures minimal dopant diffusion while maintaining crystalline perfection. After removing the device from the STM system, a polymethyl methacrylate resist and electron-beam lithography were used to define a series of small holes (200 nm in diameter) aligned with the phosphorus patches. This step was followed by reactive ion etching and aluminium lead deposition. Through these holes, the leads penetrated the dopant layer, establishing direct electrical contact between the metal and the phosphorus patches. The ohmic contacts between the buried P-dopant device and aluminium electrodes were formed through silicon vias. Then, an aluminium microwave antenna was fabricated atop the device, separated by a 10 nm atomic-layer-deposited Al_2O_3 dielectric layer to prevent current leakage and enable high-fidelity spin manipulation.

Estimation of uncertainties

All reported uncertainties correspond to 1 s.d. from the mean, estimated through 2,000 Monte Carlo bootstrap resampling trials. Specifically, we model the measured counts for each spin state (for example, $|\downarrow\downarrow\downarrow\downarrow\rangle$ to $|\uparrow\uparrow\uparrow\uparrow\rangle$) across N measurement repetitions as following a multinomial distribution. To clarify the representation of the uncertainties, we provide the following illustrative example: the value 96.5(20)% corresponds to $96.5 \pm 2.0\%$, where the number in parentheses denotes the s.d.

[[4, 2, 2]] detection code

The logical code words $|L_1 L_2\rangle$ in the computational basis are

$$\begin{aligned} |00\rangle_L &= \frac{1}{\sqrt{2}} (|0000\rangle + |1111\rangle), \\ |01\rangle_L &= \frac{1}{\sqrt{2}} (|0011\rangle + |1100\rangle), \\ |10\rangle_L &= \frac{1}{\sqrt{2}} (|0101\rangle + |1010\rangle), \\ |11\rangle_L &= \frac{1}{\sqrt{2}} (|0110\rangle + |1001\rangle). \end{aligned} \quad (1)$$

The stabilizers performing the syndrome extraction of the physical phase-flip and bit-flip errors are $\hat{S}^X = X_1 X_2 X_3 X_4$ and $\hat{S}^Z = Z_1 Z_2 Z_3 Z_4$ respectively. All logical basis states in equation (1) have even parity, while any single physical qubit errors lead to a state with odd parity.

The correspondence between logical operators and physical operators is as follows: the logical operation X_L corresponds to applying X gates on physical qubits 1 and 3 ($X_1 X_3$). Similarly, $I_L X_L$ maps to $X_1 X_2 X_3 X_4$. By contrast, the Z_L operation corresponds to $Z_1 Z_2 Z_3 Z_4$, while $I_L Z_L$ translates to $Z_1 Z_2 Z_3$. The logical Hadamard operation H_L requires H gates on all four physical qubits ($H_1 H_2 H_3 H_4$), followed by swapping of physical qubits 2 and 3 (SWAP_{23}). Finally, the logical CNOT_L is implemented as a SWAP_{12} operation, where the logical L_1 is the control qubit.

Compared with the logical operations above, the implementation of the S_L gate is less intuitive. The S_L gate is implemented by applying physical S gates to the first two physical qubits, followed by a CZ gate between them (Fig. 3a). The physical S gates accumulate the target phase on the logical qubit L_1 , while the CZ gate cancels the extra phase accumulated on physical qubits 1 and 2. For example, when the two physical S gates are applied for the first two physical qubits, with the initial state being $|\psi_0\rangle_L = |00\rangle_L + |10\rangle_L$, the corresponding physical qubit state becomes $|\psi_1\rangle = |0000\rangle + e^{i\pi} |1111\rangle + e^{i\pi/2} |0101\rangle + e^{i\pi/2} |1010\rangle$. Then, the CZ gate is applied to correct the phase accumulated on the $|1111\rangle$ state. As a result, the target logical qubit state is obtained: $|\psi_2\rangle_L = |00\rangle_L + e^{i\pi/2} |10\rangle_L$.

Quantum state tomography

The density matrix of a four-qubit state can be expressed as follows:

$$\rho = \frac{1}{16} \sum_{i,j,k,l=1}^4 c_{i,j,k,l} M_i \otimes M_j \otimes M_k \otimes M_l, \quad (2)$$

where $c_{i,j,k,l}$ denotes the expansion coefficients of the density matrix and $M_i, M_j, M_k, M_l \in \{I, X, Y, Z\}$ are the Pauli operators acting on the qubits i, j, k and l . There are $4^4 = 256$ linear independent operators in total, from $I \otimes I \otimes I \otimes I, X \otimes I \otimes I \otimes I, \dots$ to $Z \otimes Z \otimes Z \otimes Z$.

To reconstruct the density matrix, 255 expectation values are to be determined in the experiment (except for $c_{1,1,1,1} = 1$). For qubit j in the I -base measurement, no prerotation is applied after the target state $|\psi\rangle$ is prepared; for qubit k in the X -base measurement, a $R_y^k(-\pi/2)$ prerotation is applied; a $R_x^l(\pi/2)$ prerotation is applied for qubit l in the Y -base measurement; and we use I -base projection outcomes for the Z -base calculation rather than performing $R_x(\pi)$ prerotation to any qubit, to prevent rotation error⁵². All the above prerotations are realized by NMR pulses, which are conditional on the electron spin being in the $|\downarrow\rangle$ state.

After that, the maximum likelihood estimation method is used to restrict the measured density matrix to be physical (Hermitian, positive semidefinite and trace preserving) while providing the closest measurement probabilities. According to the Cholesky decomposition, a physical density matrix can be written as $\rho = T^\dagger T / \text{Tr}(T^\dagger T)$. The matrix T is a complex lower triangle matrix, which has 2^{2D} ($D=4$ for four qubits) parameters $t_1, t_2, \dots, t_{256}$. The loss function is defined as follows:

$$L(t_1, t_2, \dots, t_{256}) = \sum_{i=1}^{2^{2D}} \frac{(\langle\psi_i|\rho(t_1, t_2, \dots, t_n)|\psi_i\rangle - P_i)^2}{16 \langle\psi_i|\rho(t_1, t_2, \dots, t_n)|\psi_i\rangle}, \quad (3)$$

where P_i are the measured probabilities projected at basis $|\psi_i\rangle$. We minimize this loss function to obtain the final and physical density matrix.

All the fidelity in this paper is calculated by $F = (\text{Tr} \sqrt{\sqrt{\rho^{\text{ideal}}} \rho \sqrt{\rho^{\text{ideal}}}})^2$, where ρ^{ideal} is the corresponding ideal density matrix.

Logical density matrix reconstruction

The complete quantum state tomography reconstructs the physical density matrix, which generally contains components outside the logical subspace defined by the stabilizers $\hat{S}^X$ and $\hat{S}^Z$. The parity projection is fundamentally enabled by the projection operator $(I + I^{\otimes 4})/2$, where I represents the stabilizers of the $[[4, 2, 2]]$ code, and $I^{\otimes 4}$ denotes the four-qubit identity operator. We can project the physical density matrix into three subspaces defined by the +1 eigenspace of $\hat{S}^X$, the +1 eigenspace of $\hat{S}^Z$ and their simultaneous eigenspace. The logical density matrix is then obtained after applying the projection.

Quantum process tomography

A quantum operation can be described by the operator-sum representation, expressed as

$$\mathcal{E}(\rho) = \sum_i \alpha_i \rho \alpha_i^\dagger, \quad (4)$$

where the operation elements $\{\alpha_i\}$ satisfy the completeness condition:

$$\sum_i \alpha_i^\dagger \alpha_i = I. \quad (5)$$

To experimentally determine the operators α_i , we adopt an equivalent representation using a fixed basis $\{\tilde{\alpha}_i\}$ spanning the space of d^2 complex matrices (for N -qubit systems, $d = 2^N$). This gives the χ -matrix representation:

$$\mathcal{E}(\rho) = \sum_{mn} \chi_{mn} \tilde{\alpha}_m \tilde{\alpha}_n^\dagger, \quad (6)$$

where the $d^2 \times d^2$ matrix χ fully characterizes the quantum process. For the single-qubit system, the standard basis operators are chosen as follows:

$$\tilde{\alpha}_1 = I, \tilde{\alpha}_2 = X, \tilde{\alpha}_3 = -iY, \tilde{\alpha}_4 = Z. \quad (7)$$

Experimentally determining an arbitrary single-qubit operation requires measuring 12 parameters through input states $|0\rangle$, $|1\rangle$, $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and $|+i\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$. Quantum state tomography on the output states yields four matrices:

$$\begin{aligned} \rho'_1 &= \mathcal{E}(|0\rangle\langle 0|), \\ \rho'_4 &= \mathcal{E}(|1\rangle\langle 1|), \\ \rho'_3 &= \mathcal{E}(|+\rangle\langle +|) - i\mathcal{E}(|+i\rangle\langle +i|) - \frac{(1-i)}{2}(\rho'_1 + \rho'_4), \\ \rho'_2 &= \mathcal{E}(|+\rangle\langle +|) + i\mathcal{E}(|+i\rangle\langle +i|) - \frac{(1+i)}{2}(\rho'_1 + \rho'_4). \end{aligned} \quad (8)$$

These correspond to $\rho'_j = \mathcal{E}(\rho_j)$ with $\rho_1 = |0\rangle\langle 0|$, $\rho_2 = \rho_1 X$, $\rho_3 = X\rho_1$ and $\rho_4 = X\rho_1 X$. The linear decomposition of $\mathcal{E}(\rho_j)$ in the basis states ρ_k leads to the following relation:

$$\tilde{\alpha}_m \rho_j \tilde{\alpha}_n^\dagger = \sum_k \beta_{jk}^{mn} \rho_k, \quad (9)$$

where coefficients β_{jk}^{mn} are determined by the basis states and operators. For the single-qubit case, these relations are encapsulated in the transformation matrix:

$$\Lambda = \frac{1}{2} \begin{pmatrix} I & X \\ X & -I \end{pmatrix}. \quad (10)$$

The χ -matrix is then constructed through block matrix operations:

$$\chi = \Lambda \begin{pmatrix} \rho'_1 & \rho'_2 \\ \rho'_3 & \rho'_4 \end{pmatrix} \Lambda. \quad (11)$$

The process fidelity definition we used here is

$$F_\chi = \left(\text{Tr} \sqrt{\sqrt{\chi^{\text{ideal}}} \chi \sqrt{\chi^{\text{ideal}}}} \right)^2, \quad (12)$$

where χ^{ideal} is the ideal process matrix.

Classical optimizer

For the classical optimizer, we employed the Nelder–Mead algorithm⁵³ for optimization, which is a simplex-based direct-search method suitable for unconstrained minimization of objective functions. Compared with other direct-search methods such as gradient descent that may exhibit better convergence on smooth functions, Nelder–Mead demonstrates robustness for noisy functions and can explore nearby valleys, thereby avoiding local minima trapping and overcoming non-smoothness of objective functions.

We improved the Nelder–Mead algorithm to suit our specific experimental situation. To enforce the algorithm's angular domain constraint of $[-\pi, \pi)$, we applied periodic boundary conditions by computationally wrapping the optimization parameter θ (Fig. 5a) into this interval during each iterative optimization step. Furthermore, we optimized the Nelder–Mead algorithm's reflection, expansion, contraction and shrink coefficients to achieve convergence to the global minimum with fewer iterations.

Clifford fitting

To reduce the impact of noise in near-term quantum computations, error mitigation techniques process noisy results to more accurately estimate ideal expectation values⁵⁴. Clifford fitting is also referred to as Clifford data regression^{50,55}. The core idea is to learn a correction function, f^{CF} , using training data generated from efficiently simulatable Clifford circuits. For these circuits, both the noisy expectation values (χ^{noisy}) measured on hardware and the exact expectation values (χ^{exact}) computed classically are obtained. The function f^{CF} is determined by fitting these data pairs. Subsequently, this learned function is applied to the noisy result measured for the actual target circuit, for which an exact value may be hard to compute. Specifically, given the noisy measurement χ_ψ^{noisy} for a target state $|\psi\rangle$ (prepared by circuit U_ψ) and observable X , Clifford data regression aims to find f^{CF} to approximate the ideal value $\chi_\psi^{\text{exact}} = \langle \psi | X | \psi \rangle$ via the following relation:

$$\chi_\psi^{\text{corrected}} = f^{\text{CF}}(\chi_\psi^{\text{noisy}}, \vec{a}) \approx \chi_\psi^{\text{exact}}, \quad (13)$$

where $\vec{a}$ represents a set of parameters characterizing the function f^{CF} .

In the VQE experiment, we implement Clifford fitting in a quantum parameterized circuit. First, according to the method in ref. 50, we distinguish between observables that vary with parameters and those that remain constant. Constant observables cannot be analysed using the Clifford fitting method. Let M denote the number of parameterized gates. Then, by randomly selecting K gates from M , we independently and uniformly sample their K parameters from the range $[-\pi, \pi)$, while the remaining $M-K$ gates are converted into identity operations. This process generates m random circuits $\{S_i^{(K)}\}_{i=1}^m$. The number m should be sufficient (typically over 10) to ensure an adequate fitting performance of $\vec{a}$ in the linear regression. The dataset consists of pairs of noisy and exact expectation values $\mathcal{T}_\psi = \{(\chi_\psi^{\text{noisy}}, \chi_\psi^{\text{exact}})\}$, generated from a set of quantum circuits $\{S_i^{(K)}\}_{i=1}^m$. Thus, the parameters $\vec{a}$ of the correction function f^{CF} can be fitted by the linear regression function

$$f^{\text{CF}}(\chi_\psi^{\text{noisy}}, \vec{a}) = a_1 \chi_\psi^{\text{noisy}} + a_2. \quad (14)$$

The parameters a_1 and a_2 are typically determined by minimizing the least-squares cost function

$$C = \sum_i (\chi_{\psi_i}^{\text{exact}} - (a_1 \chi_{\psi_i}^{\text{noisy}} + a_2))^2. \quad (15)$$

There is theoretical justification for the linear model, as it can perfectly correct for certain noise models, such as global depolarizing noise.

Finally, after determining the optimal parameters $\vec{a}^* = (a_1^*, a_2^*)$, the error-mitigated expectation value for the original target circuit is predicted using equation (13):

$$\chi_\psi^{\text{corrected}} = a_1^* \chi_\psi^{\text{noisy}} + a_2^*. \quad (16)$$

Symmetry verification

Molecular Hamiltonians in quantum simulations inherently possess symmetry constraints such as particle number conservation. Symmetry verification through subspace expansion provides an effective error mitigation strategy. Following the methodology in ref. 56, we

implement this approach for the $[[4, 2, 2]]$ code. For a general $[[n, k, d]]$ code, the code space is defined by the projection operator:

$$\hat{P} = \prod_{i=1}^l P_i = \frac{1}{2^l} \sum_{M_i \in S} M_i, \quad (17)$$

where $l = n - k$; $P_i = \frac{1}{2}(I + u_i)$ projects onto the +1 eigenspace of stabilizer generators $u_i \in G = \langle u_1, \dots, u_l \rangle$; and S denotes the stabilizer group. For a code-space Hamiltonian $H_c = \sum_i \gamma_i \Gamma_i$, where γ_i denotes the coefficient of the i th term, and Γ_i represents the corresponding Pauli string operator, the symmetry-verified expectation value becomes the following:

$$\langle H_c \rangle = \frac{1}{c 2^l} \sum_{j,k} \gamma_j \text{Tr} [\rho \Gamma_j M_k], \quad (18)$$

where $c = \text{Tr}[\hat{P}\rho]$ normalizes the density matrix ρ projected onto the symmetry-preserving subspace.

Data availability

The data relevant to this study are available via Zenodo at <https://doi.org/10.5281/zenodo.15599599> (ref. 57). Source data are provided with this paper.

Code availability

All the code relevant to this work is available from the corresponding authors upon reasonable request.

References

52. Watson, T. F. et al. A programmable two-qubit quantum processor in silicon. *Nature* **555**, 633–637 (2018).
53. Nelder, J. A. & Mead, R. A simplex method for function minimization. *Comput. J.* **7**, 308–313 (1965).
54. Endo, S., Cai, Z., Benjamin, S. C. & Yuan, X. Hybrid quantum-classical algorithms and quantum error mitigation. *J. Phys. Soc. Jpn* **90**, 032001 (2021).
55. Czarnik, P., Arrasmith, A., Coles, P. J. & Cincio, L. Error mitigation with Clifford quantum-circuit data. *Quantum* **5**, 592 (2021).
56. McClean, J. R., Jiang, Z., Rubin, N. C., Babbush, R. & Neven, H. Decoding quantum errors with subspace expansions. *Nat. Commun.* **11**, 636 (2020).
57. Zhang, C. & Xu, F. Source data for ‘Universal logical operations in a silicon quantum processor’. *Zenodo* <https://doi.org/10.5281/zenodo.15599599> (2025).

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Author contributions

Y.H. and D.Y. supervised this project. M.D., Z.T., K.S., H.W., B.Z., H.S., Y.-N.Z., J.L. and K.W. fabricated the device, with T.P., G.W., Y.H. and S.L.’s supervision. C.Z., F.X. and C.L. performed the experiments and analysed the data, with G.H. and Y.H.’s supervision. X.B., C.H., Y.D., M.G. and Y.J. analysed the data and plotted figures, with G.H. and Y.H.’s supervision. S.Z., P.H., C.Z., F.X. and T.X. analysed and designed the compiling schemes of the quantum circuits. S.Z. developed methods to mitigate the cross-talk errors and tools to calculate the dynamics of the quantum circuits under P.H.’s supervision. Under T.X. and X.Y.’s supervision, F.X. and C.Z. formulated state and process tomography methods, and F.X., D.Z. and Q.D. developed VQE schemes. Y.H., T.X., P.H., G.H., C.Z., F.X., S.Z., G.W. and Z.T. wrote the paper, with input from all coauthors. The paper was revised by all the authors.

Competing interests

The authors declare no competing interests.

Additional information

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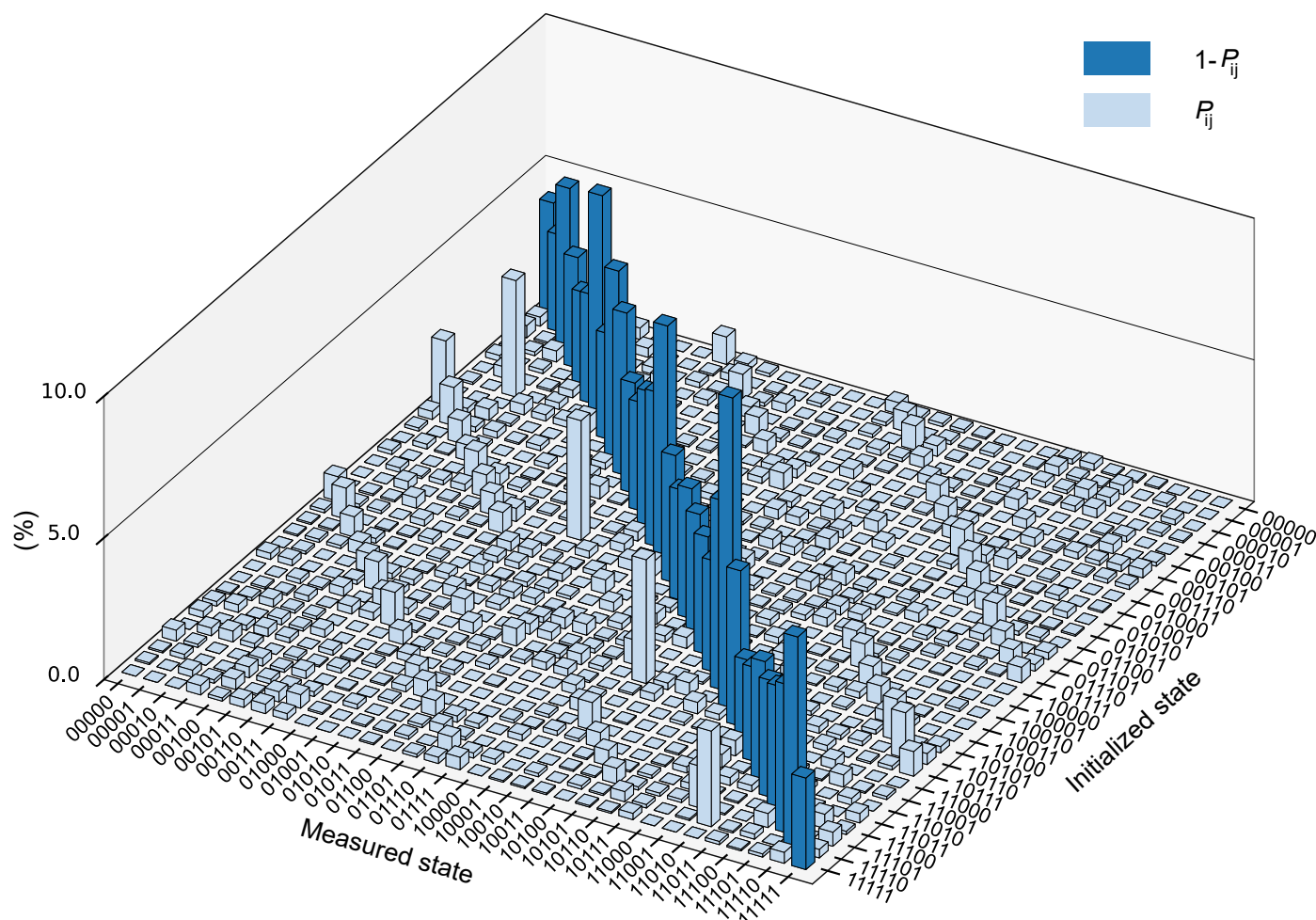
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Extended Data Table 1 | Fidelity characterizations of all involved logical states and logical operations

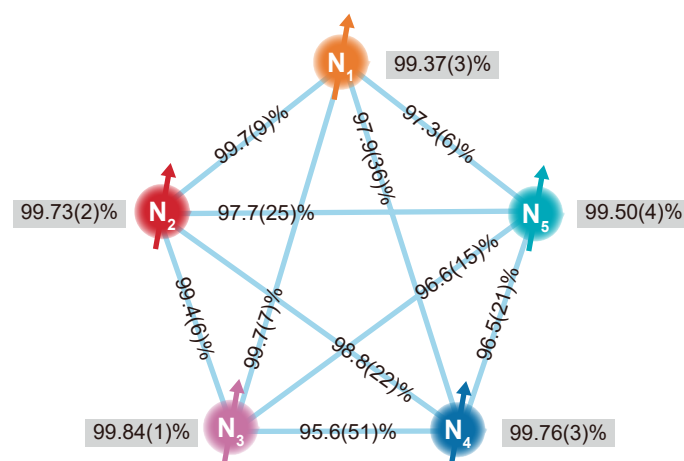
Logical operation	State	Characteristic	Physical fidelity (%)	Logical fidelity (%)	Acceptance (%)
Preparation	$ 00\rangle_L$	FT	84.2(5)	96.5(6)	83.9(13)
	$ \Phi'\rangle_L$	FT	80.5(7)	95.5(9)	82.9(17)
	$ 00\rangle_L$	FT (flag with 0 and 1)	60.9(6)	95.7(10)	60.1(14)
	$ 00\rangle_L$	FT (flag with 1)	67.6(6)	97.3(7)	66.5(16)
	$ 00\rangle_L$	nFT	72.6(6)	90.4(14)	66.9(33)
	$ 10\rangle_L$	nFT	76.2(9)	92.8(9)	74.6(19)
	$ +0\rangle_L$	nFT	75.0(9)	96.5(11)	72.5(24)
	$ +i0\rangle_L$	nFT	72.2(8)	91.4(13)	70.1(20)
$T_L I_L$	$ 00\rangle_L$	nFT ($Q_a = 0$)	54.7(15)	87.7(14)	58.9(19)
	$ 10\rangle_L$	nFT ($Q_a = 0$)	53.3(14)	89.5(20)	51.4(23)
	$ +0\rangle_L$	nFT ($Q_a = 0$)	57.5(13)	89.8(21)	57.9(24)
	$ +i0\rangle_L$	nFT ($Q_a = 0$)	60.7(20)	84.0(23)	62.2(26)
$T_L' I_L$	$ 00\rangle_L$	nFT ($Q_a = 1$)	60.6(18)	88.4(21)	58.6(27)
	$ 10\rangle_L$	nFT ($Q_a = 1$)	63.7(14)	97.5(11)	63.5(21)
	$ +0\rangle_L$	nFT ($Q_a = 1$)	64.0(15)	89.7(23)	63.7(29)
	$ +i0\rangle_L$	nFT ($Q_a = 1$)	74.5(16)	95.2(19)	66.7(31)
$S_L I_L$	$ 00\rangle_L$	nFT	60.3(9)	87.5(13)	64.4(19)
	$ 10\rangle_L$	nFT	72.7(10)	95.1(8)	71.9(19)
	$ +0\rangle_L$	nFT	64.0(10)	86.4(15)	66.1(19)
	$ +i0\rangle_L$	nFT	65.3(9)	90.9(15)	64.0(24)

The logical operation column denotes the operations applied to corresponding logical states. Flag with 0 and 1 indicates postselection ignoring flag qubit measurement outcomes, while flag with 1 specifies filtering data with flag qubit measurement outcome $|1\rangle$ (~ 13.2% data discard). Q_a denotes the ancillary qubit for $T_L I_L$ and $T_L' I_L$ manipulation. $Q_a=1$ corresponds to data postselected with Q_a measurement outcome $|1\rangle$, while $Q_a=0$ represents data with the measurement results of filtering Q_a of $|0\rangle$. The definition of the acceptance is given in the Supplementary Information Sec. S7.



Extended Data Fig. 1 | SPAM characterization. SPAM matrix of the five nuclear spin qubits $N_1 - N_5$. The SPAM matrix can be extracted by projecting each initialized state into 2^5 measurement bases. Each initialized state is measured for 1,900 trials to determine the corresponding probabilities P_{ij} , where P_{ij} denotes the measured probability in state $|i\rangle$ when initialized in state $|j\rangle$. To highlight the error, $1 - P_{ij}$ is plotted for the diagonal element (dark blue). After summing all the

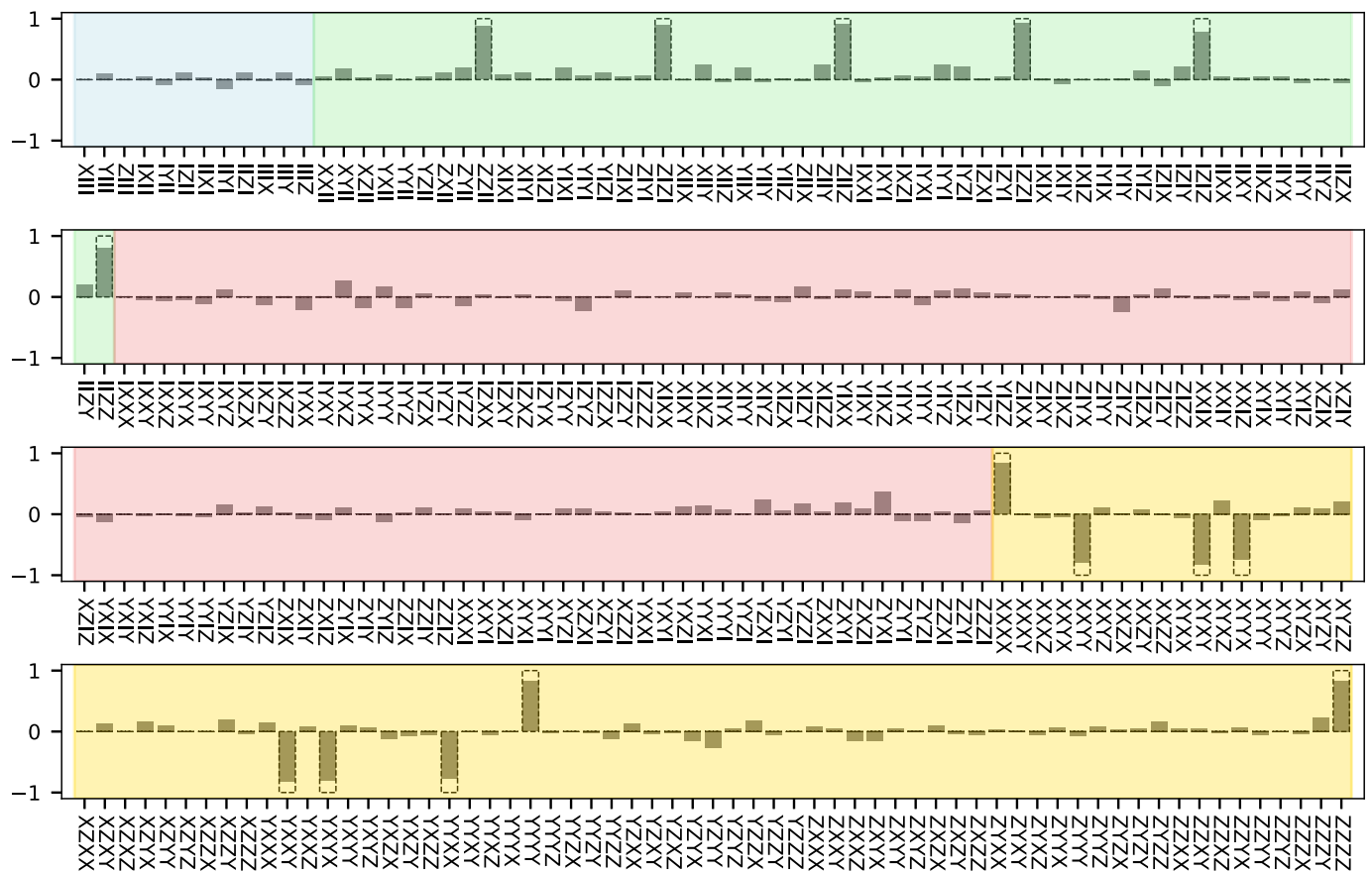
probabilities over all states corresponding to the target qubit transition from $|0\rangle$ to $|1\rangle$, while tracing out the other qubits, the SPAM errors for each qubit are obtained as: $P_{10}^{N_1} = 1.17\%$, $P_{01}^{N_1} = 1.20\%$; $P_{10}^{N_2} = 1.01\%$, $P_{01}^{N_2} = 1.10\%$; $P_{10}^{N_3} = 0.94\%$, $P_{01}^{N_3} = 2.20\%$; $P_{10}^{N_4} = 2.24\%$, $P_{01}^{N_4} = 2.23\%$; $P_{10}^{N_5} = 2.09\%$, $P_{01}^{N_5} = 2.35\%$, respectively. Additionally, the SPAM error can be mitigated via the inversion of this matrix⁴⁸.



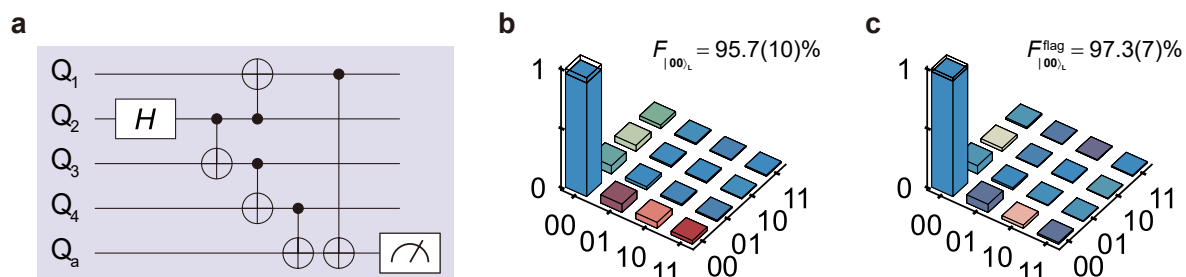
Extended Data Fig. 2 | Gate fidelities of the high connectivity qubit system.

Here, a controlled-Z (CZ) gate can be implemented between any pair of nuclear spins via the shared electron. The values on the connecting lines (skyblue) represent CZ gate fidelities characterized by the interleaved randomized benchmarking (IRB). For each benchmarking result, over 10 distinct RB/IRB gate

sequences are randomly generated, and each sequence is measured with 100 independent repetitions. Additionally, the single-qubit RB fidelities are shown in the shaded gray boxes adjacent to each nuclear spin. All error bars (1σ) are derived from the Monte Carlo bootstrap resampling method.

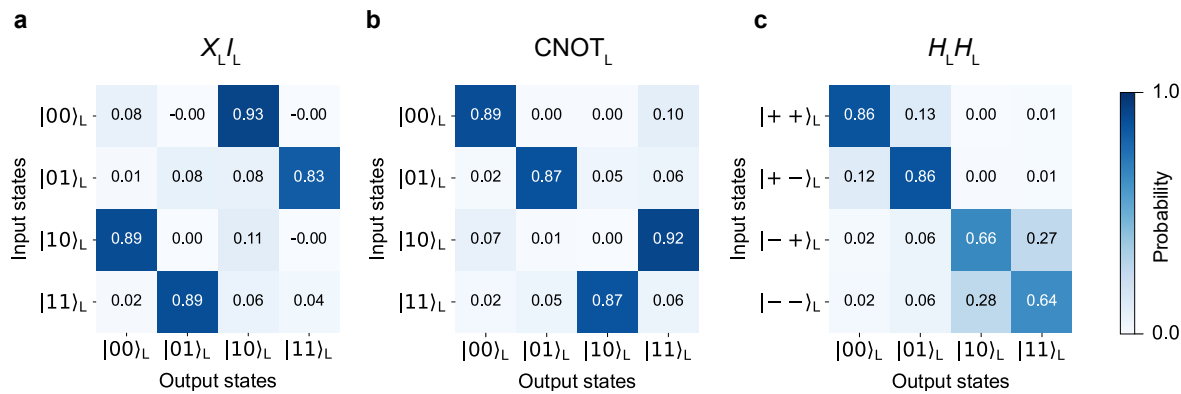


Extended Data Fig. 3 | Four-qubit quantum state tomography. Measured 255 expectation values for FT prepared logical $|00\rangle_L$ state, which are used to reconstruct the density matrix. Dashed box indicates the ideal expectation values for each observable.

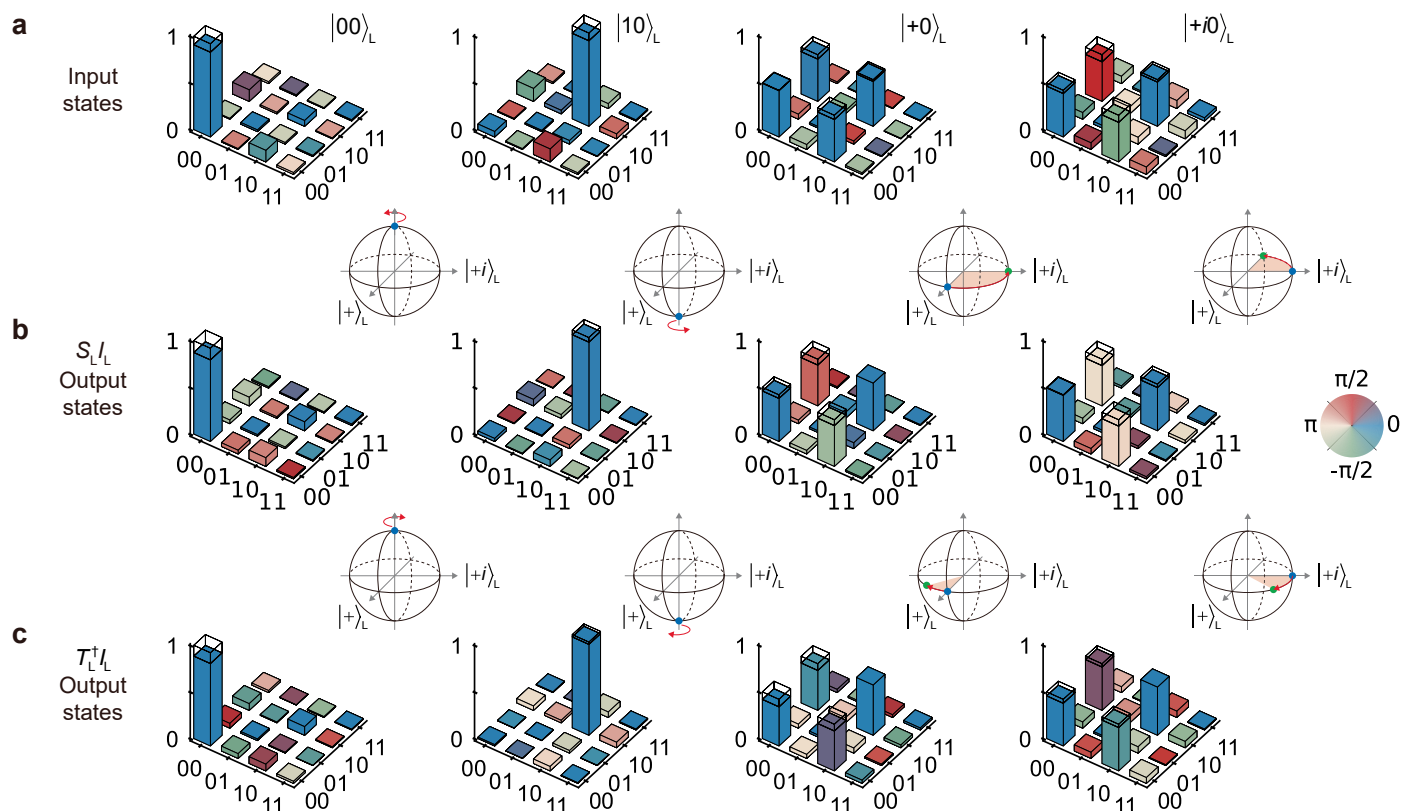


Extended Data Fig. 4 | FT preparation for Gottesman's proposal. a, Circuit for logical $|00\rangle_L$ state FT preparation with a flag qubit Q_a . **b,** The density matrix for $|00\rangle_L$, which is obtained by the quantum state tomography and postprocessed

with $\hat{S}^Z$ and $\hat{S}^X$ stabilizers, yielding a fidelity $F_{|00\rangle_L} = 95.7(10)\%$. **c,** After postselecting the cases with unraised flag results (retaining ~86.8% data) from **b**, the fidelity improves to $F_{|00\rangle_L}^{\text{flag}} = 97.3(7)\%$.

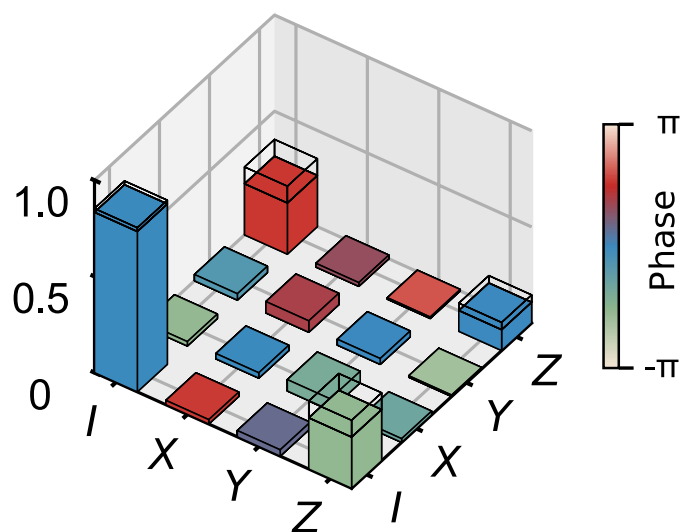


Extended Data Fig. 5 | State population transfer matrices. a-c, The state population transfer matrices for $X_L I_L$, $CNOT_L$, and $H_L H_L$ logical operations, yielding 88.3(5)%, 88.6(4)%, and 75.6(4)% population transfer fidelities, respectively. The emergence of non-physical negative values can be attributed to higher-order residuals after the SPAM error mitigation.

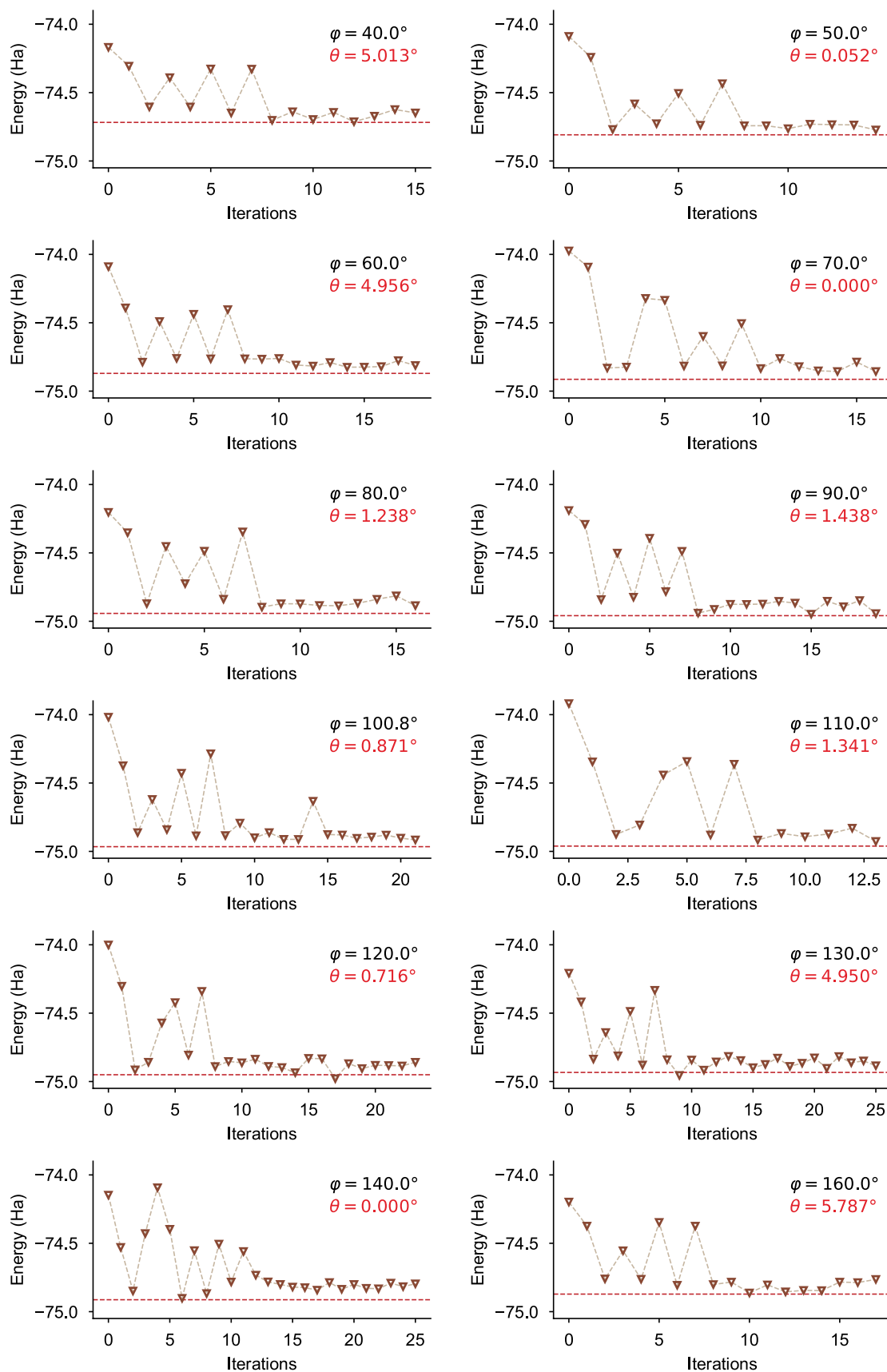


Extended Data Fig. 6 | Logical states density matrices used for QPT characterization of $S_L I_L$ and $T_L^\dagger I_L$ gates. **a**, Quantum state tomography results for the four input logical cardinal states $|00\rangle_L$, $|10\rangle_L$, $|+0\rangle_L$, $|+i0\rangle_L$. **b**, The corresponding

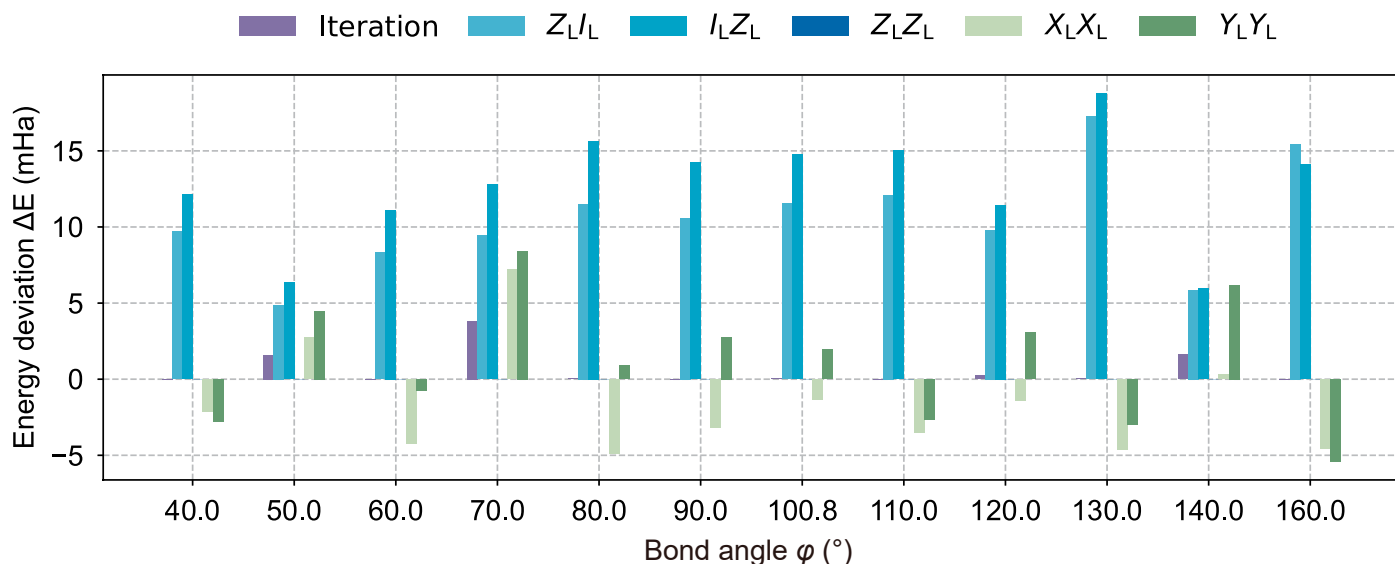
output states after applying $S_L I_L$ to each input state. **c**, The corresponding output states after applying $T_L^\dagger I_L$ to each input state with the ancillary qubit Q_2 outcomes $|1\rangle$. Inset depicts the rotation processes on the Bloch spheres.



Extended Data Fig. 7 | QPT matrix of $T_L^\dagger I_L$ gate. The $T_L^\dagger I_L$ gate is measured with the ancillary qubit Q_a outcomes $|1\rangle$, revealing a gate process fidelity of 91.5(24)%.



Extended Data Fig. 8 | Iteration processes for different bond angles ϕ . The optimal angle θ (denoted in red) of the rotation gate $R_y(\theta)$ in Fig. 4a corresponds to the angle with the minimum energy in the iterative process.



Extended Data Fig. 9 | Error distributions across different bond angles of the water molecule. The experimental procedure is detailed in Supplementary Information Sec. S10. Despite employing various error mitigation techniques, the final VQE results exhibit a residual error of approximately 20 mHa relative to the ground-state energy $E_{\min}$ obtained via exact diagonalization of the water Hamiltonian H . Here, the iteration error quantifies the discrepancy between $E_{\min}$ and the energy computed from the ideal circuit parameterized by the experimentally optimized angles θ_{opt} . The error components arising from the observables ($Z_L I_L$, $I_L Z_L$, $Z_L Z_L$, $X_L X_L$, and $Y_L Y_L$) are defined as deviations between

experimentally measured expectation values and their theoretical counterparts derived from $E_{\min}$. Critically, the iteration error remains below 5 mHa for all bond angles, confirming both the efficacy of the iterative optimization protocol and its robustness to experimental noise. We applied the angle of the rotation gate $R_y(\theta)$ (see Fig. 5a) derived from the noiseless iteration process in the master equation simulations (see Supplementary Information Sec. S12). The dominant error contributions stem from the $Z_L I_L$ and $I_L Z_L$ observables, primarily arising from decoherence and frequency cross-talk between qubits (see the simulation results in Fig. 5b).